

Forward-backward flow correlations in relativistic heavy-ion collisions^{*)}

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We discuss the torque effect in the initial fireball formed in relativistic heavy-ion collisions, manifesting itself, on the event-by-event basis, in a relative angle between the principal axes of the transverse momentum distributions in the forward and backward rapidity regions. The torque follows from two natural features: 1) the sources of particles (e.g. wounded nucleons) emit predominantly in their forward hemispheres, and 2) there exist fluctuations in the transverse distribution of sources from the two colliding nuclei. On the average, the standard event-by-event deviation of the relative torque angle is about 20° for the central and 10° for the mid-peripheral collisions. The hydrodynamic expansion of a torqued fireball leads to a torqued collective flow of the fluid, which, in turn, yields torqued principal axes of the transverse-momentum distributions at different rapidities. We discuss experimental measures based on cumulants involving particles in different rapidity regions, which allow for a quantitative extraction of the effect from the experimental data. We estimate the non-flow contributions from resonance decays with the help of THERMINATOR.

The forward-backward rapidity correlations reveal important information on the mechanism of particle production in high-energy hadronic and nuclear collisions, uncovering the features of the dynamical system at a very early stage. This talk is based on our recent work,¹⁾ where more details as well as a complete list of references may be found. We discuss an interesting forward-backward effect, concerning the event-by-event fluctuations of the longitudinal shape of the fireball created in relativistic heavy-ion collisions.

The effect relies on two basic facts: 1) The wounded nucleons²⁾ emit particles predominantly in their forward hemispheres (see Fig. 1) – this feature is strongly supported with the data analyses of the d-Au³⁾ and AA⁴⁾ collisions, as well as a successful (for the first time) description of the directed flow⁵⁾ at RHIC. 2) There are random fluctuations as explained in Fig. 2. The key point here is that the number of wounded nucleons in a cluster may be asymmetric, i.e., it may contain more nucleons from nucleus A than B. Since the emission profiles are asymmetric, the torque of the principal axes is higher in the direction of motion where more wounded nucleons are moving. As a result, the initial fireball is torqued on the event-by-event basis, as graphically shown in Fig. 3. Specifically, we use the mixed model of the initial Glauber phase, adding 14% of binary collisions to the wounded nucleons.¹⁾

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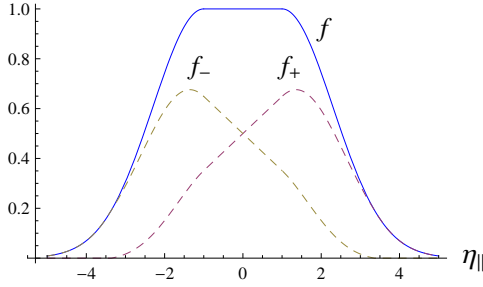


Fig. 1. The emission profiles in space-time rapidity $\eta_{||}$ for the wounded nucleons (dashed lines) and the binary collisions (solid line). The profiles f_+ and f_- corresponds, respectively, to the forward and backward moving wounded nucleons.

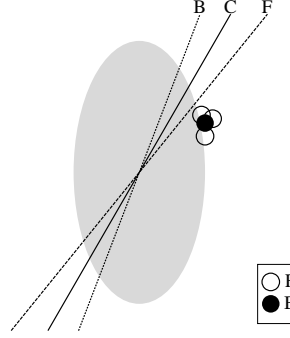


Fig. 2. Emergence of the torque effect: A random cluster of wounded nucleons moving in the forward (F) and backward (B) directions causes a random torque of the principal axes. The angle is higher in the forward direction than in the backward direction. (C) indicates the central region.

The initial fireball is then evolved hydrodynamically (here we use perfect 3+1 dimensional hydrodynamics with a realistic equation of state), which leads to a torque in the collective flow velocity. This, in turn, yields a torque of the principal axes (between the forward and backward regions) of the measured transverse-momentum distributions of created hadrons. Since statistical hadronization leads to random fluctuations of the direction of principal axes, one needs to look at the torque effect and the prospects of its experimental observation with care. For that purpose we have proposed¹⁾ to consider cumulant measures involving particles from the forward and backward regions. Let

$$\left\langle e^{in(\phi_F - \phi_B)} \right\rangle = \frac{1}{N_{\text{events}}} \sum_{\text{events}} \frac{1}{n_F n_B} \sum_{i=1}^{n_F} \sum_{j=1}^{n_B} e^{ik(\phi_i - \phi_j)}, \quad (1)$$

with k denoting the Fourier rank and ϕ_i (ϕ_j) being the azimuthal angles of particles emitted in the forward (backward) rapidity windows. The quantities n_F and n_B are the corresponding multiplicities and N_{events} is the number of events. When no correlations between particles are present, the distribution function of n particles is the product of one-body distributions

$$f(\phi) = v_0 + 2 \sum_{k=1} v_k \cos[k(\phi - \Psi^{(k)})], \quad (2)$$

and one obtains

$$\left\langle e^{ik(\phi_F - \phi_B)} \right\rangle = \langle v_{k,F} v_{k,B} \cos(k \Delta_{FB}) \rangle_{\text{events}}, \quad (3)$$

where $\Delta_{FB} = \Psi_F^{(k)} - \Psi_B^{(k)}$ is the relative torque angle between the principal axes in the forward and backward directions. Non-flow (nf) contributions (resonance decays, jets, conservation laws, Bose-Einstein correlations, short-range correlations,

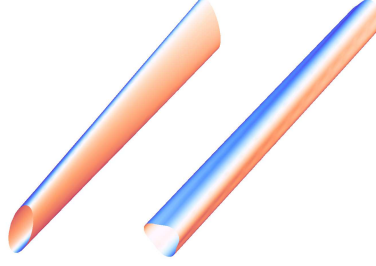


Fig. 3. The schematic figure of the torqued fireball, elongated along the η_{\parallel} axis. The direction of the principal axes in the transverse plane rotates as $|\eta_{\parallel}|$ increases. The left and right pictures correspond to the rank-2 (elliptic) and rank-3 (triangular) cases, respectively. The effect occurs on event-by-event basis.

etc.) modify the right-hand side of Eq. (3) at the level $1/n$, where n denotes the effective multiplicity. Since we are interested in $\cos[k(\Psi_F - \Psi_B)]$, we divide Eq. (3) by $v_{k,F}v_{k,B}$ by evaluating the following ratio of cumulants:

$$\cos(k\Delta_{FB}) \{2\} \equiv \frac{\langle e^{ik(\phi_F - \phi_B)} \rangle}{\sqrt{\langle e^{ik(\phi_{F,1} - \phi_{F,2})} \rangle \langle e^{ik(\phi_{B,1} - \phi_{B,2})} \rangle}} = \langle \cos(k\Delta_{FB}) \rangle_{\text{events}} + \text{nf.} \quad (4)$$

One may also use higher-order cumulants to generate statistical measures of the torque. For example, the ratio of four-particle cumulants yields

$$\cos(2k\Delta_{FB}) \{4\} \equiv \frac{\langle e^{ik[(\phi_{F,1} + \phi_{F,2}) - (\phi_{B,1} + \phi_{B,2})]} \rangle}{\langle e^{ik[(\phi_{F,1} - \phi_{F,2}) - (\phi_{B,1} - \phi_{B,2})]} \rangle} = \langle \cos(2k\Delta_{FB}) \rangle_{\text{events}} + \text{nf.} \quad (5)$$

The important issue in such of studies is the influence of the non-flow contributions.

We have run **THERMINATOR**⁶⁾ simulations on top of the hydrodynamic solutions, taking the case without the torque and with the torque, fixing the torque angle to a typical value of 8° at centrality 20-25%. The results are displayed in Figs. 4 and 5. The solid line represents the fireball torque angle of the velocity distribution after the hydrodynamic evolution. The agreement of the line and the squares shows that the statistics is sufficient to detect the torque effect. We note a sizable departure of the no-torque and torque cases in Fig. 5, showing that the effect may be observed in experimental data.

In conclusion, we summarize our results: 1) The space-time rapidity emission profile, where the initial longitudinally-moving sources emit predominantly in the direction of their motion, combined with the statistical fluctuations of the source densities in the transverse plane, lead to event-by event torqued fireballs. 2) The standard deviation of the relative torque angle in the fireball between the forward ($\eta_{\parallel} \sim 3$) and backward ($\eta_{\parallel} \sim -3$) regions varies from $\sim 20^\circ$ for the most central collisions to $\sim 10^\circ$ for the mid-central and mid-peripheral Au+Au collisions at the highest RHIC energies. 3) The torque of the initial fireball yields, via hydro evolution, the torque of the transverse fluid velocity, and, finally, turns into the torque of the principal axes of the transverse-momentum distributions of the produced hadrons.

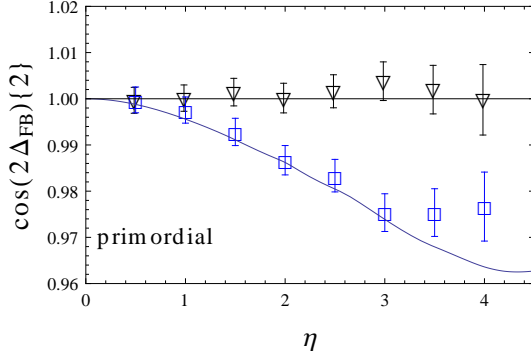


Fig. 4. THERMINATOR simulations (100000 events) for Au+Au collisions at the highest RHIC energy for $c = 20 - 25\%$. The cumulants are evaluated with the primordial particles only (i.e. with no resonance decays). Triangles correspond to the case with no torque, squares to case with the torque.

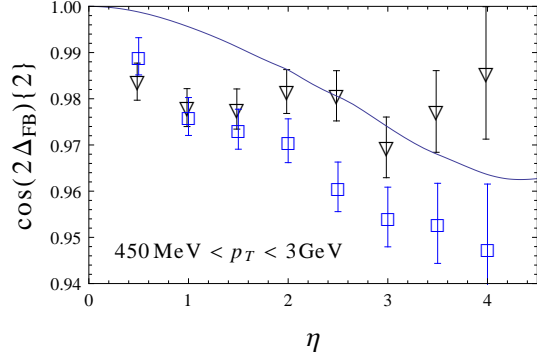


Fig. 5. Same as Fig. 4 from all final charged pions, kaons, protons, and antiprotons, with $450 \text{ MeV} < p_T < 3 \text{ GeV}$. The departure of the triangles (no torque) from unity displays the non-flow contribution from resonance decays. The torqued case (squares) is visibly shifted from the case without the torque (triangles).

4) We have proposed measures based on cumulants containing particles in different pseudorapidity bins can be used to detect the torque effect experimentally. Based on THERMINATOR simulations we expect that the torque fluctuations should be observed in the high-statistics RHIC data. 5) The statistical noise at hadronization decreases as the product of the square root of the particle multiplicity and the flow coefficient,¹⁾ hence it is best to look for the torque effect in the mid-central classes, such as $c = 20 - 30\%$, and with the exclusion of the soft-momentum hadrons to avoid correlations from resonances. 6) The torque should have a similar size for the elliptic flow and the triangular flow. 7) Other models of the initial phase (multi-source models) should also be investigated in that regard, as emergence of the effect is generic for asymmetric rapidity emission profiles.

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